

Effect of thermalized charm on heavy quark energy loss

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The recent experimental results on the flow of J/ψ at LHC show that ample amount of charm quarks is present in the quark gluon plasma and probably they are thermalized. In the current study we investigate the effect of thermalized charm quarks on the heavy quark energy loss to leading order in the QCD coupling constant. It is seen that the energy loss of charm quark increases due to the inclusion of thermal charm quarks. Running coupling has also been implemented to study heavy quark energy loss and we find a modest increase in the heavy quark energy loss due to heavy-heavy scattering at higher temperature to be realized at LHC energies.

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INTRODUCTION

The genesis of a novel state of matter, the quark-gluon plasma (QGP) presumably formed in the recent experiments at the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) provides us a scope to investigate the physics of hot and/or dense partonic matter [1]. One of the excellent probes of QGP, formed in such collider experiments, is the quenching of jet as first anticipated by Bjorken [2]. The jet quenching or in other words the energy loss of the fragmenting partons at high transverse momentum (p_T) causes depopulation of hadrons in high p_T region. Most of the calculations of light hadrons (π, η) consider the energy loss due to the induced bremsstrahlung radiation and this reproduces the experimentally observed nuclear suppression in $Au + Au$ collisions for center of mass energy $\sqrt{s_{NN}} = 62 - 200$ GeV at RHIC [3]. But recent data from the PHENIX Collaboration [4] reveal that non-photonic single electron spectrum from heavy meson decays shows larger suppression than expected. This amount of suppression cannot be explained by radiative energy loss alone because the energy loss of the heavy quark becomes small due to dead cone effect. Thus, in this context, it will be worthwhile to revisit the importance of collisional energy loss of heavy quarks.

The calculation of collisional energy loss of heavy fermion in Quantum Electrodynamics (QED) or QCD plasma has already been studied since past few years [5–16]. Heavy quarks (Q) are the important analysing tool of the primordial state of matter as they are produced early in the time scale from the initial fusion of partons and do not influence the bulk properties of the matter. In all the previous estimations mentioned above, the presence of thermalized charm quarks in the medium has been neglected. But current experimental evidences from ALICE reveal the fact that even heavy quarks along with the light quarks (q) and gluons (g) could be a possible composition of the medium and their impact on different physical quantities can not be ruled out.

Recently the ALICE collaboration has reported a value of $0.58 \pm 0.01(stat) \pm 0.09(syst)$ for the Nuclear Modification Factor (R_{AA}) of J/ψ measured for $Pb - Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the Muon spectrometer ($2.5 < y < 4$) [17]. However, at low transverse momentum ($p_T < 4$ GeV), significantly larger values of R_{AA} were measured compared to the measurements at lower energies in RHIC. This observation indicates a substantial contribution to the J/ψ production from charm quark recombination. The same data also indicates a non-zero elliptic flow coefficient (v_2) with a largest value of $0.116 \pm 0.046(stat) \pm 0.029(syst)$ for J/ψ in the transverse momentum range $2 \leq p_T < 4$ GeV/c [18]. These two observations seem to suggest a significant presence of thermalized charm quarks in the deconfined partonic matter produced in the $Pb - Pb$ collisions. Consequently these findings demand further modification of formalism of heavy quark energy loss with thermalized $c\bar{c}$ pairs taken into consideration. We, in the current study develop a complete theoretical framework to evaluate the energy loss of an energetic heavy quark including all possible scatterings with the medium particles to the leading order in the QCD coupling constant (α_s).

In all the previous studies it has been established that in the medium the heavy flavor energy loss is plagued with infrared divergences. In the non-relativistic plasma, this can be removed with the help of the Coulomb or electric interaction. However, the problem becomes nontrivial with the relativistic plasma where both the electric and the magnetic interactions are important. To circumvent the problem, the usual way is to implement Braaten and Yuan's prescription [19]. In this prescription, one separates the integration into two domains with an arbitrary cut off momentum scale q^* ($gT \ll q^* \ll T$) where $g^2 = 4\pi\alpha_s$ and T is defined as the temperature of the partonic medium. In the domain of exchange of hard gluons, (where, momentum (q) transfer $q \sim T$) one uses a tree level propagator and in the region of soft transfer (where $q \sim gT$) hard thermal loop (HTL) corrected propagator is required to provide the necessary screening from the infra-red (IR) divergence at the Debye scale gT [20, 21]. It is important to note that both the contributions from the hard as well as the soft sectors must be added together to cancel the intermediate momentum scale making the final result independent of this arbitrary cut-off parameter [9]. In the current paper, we adopt the method of Braaten and Yuan to compute heavy quark energy loss.

We also incorporate the effects of running coupling (α_{eff}) in the calculation. In QCD medium, effective field theory imposes running of the coupling constant instead of a fixed one at very high temperature ($T \gg \Lambda_s$). Implementation of running coupling has already been used to compute various physical quantities since past few years [14, 22–25]. Here, we employ the parametrization of α_{eff} in the time-like sector from Ref.[26] by extending it to the space-like sector [22, 23, 26]. This is a non-perturbative technique where α_{eff} remains finite even in the infrared domain [26]. The computation of heavy quark energy loss with thermalized $c\bar{c}$ in the medium using α_{eff} is another new component of the current manuscript. These improvisations aim at studying the experimental values of $R_{AA}(p_T)$ and $v_2(p_T)$ complementing the theoretical predictions.

I. COLLISIONAL ENERGY LOSS

The motion of a heavy quark in partonic matter looks similar to that of a test particle in the plasma. Hence, its motion can be treated as a typical Brownian motion problem. The kinematics of the test particle in the plasma can

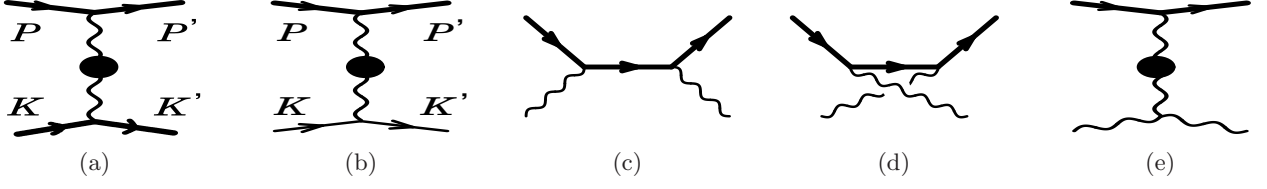


FIG. 1: Amplitudes for heavy quark elastic scattering in a QCD plasma. Fig.(a) corresponds to heavy quark-heavy quark scattering. Diagrams (b), (c), (d) and (e) correspond to Qq and Qg scatterings in s, t and u channels. The blob in (a), (b) and (e) denotes the resummed hard thermal loop boson propagator, which is required to screen the t -channel contribution in the infrared domain.

be described by Boltzmann equation. In this current scenario, since there are no external forces and the system is homogeneous, Boltzmann equation reduces to,

$$\frac{\partial f_p}{\partial t} = -\mathcal{C}[f_p], \quad (1)$$

where the right hand side of the above equation represents the collision integral. In the present paper, we consider a high energy heavy (Q) quark of mass m_1 , energy E_p and momentum p propagating through a plasma consisting light quarks (q), gluons (g) and charm quark in equilibrium at a temperature T . The injected heavy quark has small fluctuating part ($\delta f_p, f_p^0 \gg \delta f_p$) which vanishes suffering collisions with other particles of the medium. In the present work, we only consider $2 \rightarrow 2$ ($P + K \rightarrow P' + K'$) scattering processes. The explicit form of the collision integral then becomes,

$$\begin{aligned} \mathcal{C}[f_p] = & \frac{1}{2E_p} \int \frac{d^3k}{(2\pi)^3 2E_k} \frac{d^3p'}{(2\pi)^3 2E'_p} \frac{d^3k'}{(2\pi)^3 2E'_k} \delta f_p [PSF] \\ & \times (2\pi)^4 \delta^4(P + K - P' - K') \frac{1}{2} \sum_{spin} |\mathcal{M}|^2, \end{aligned} \quad (2)$$

where, [PSF] denotes the phase space factor. $|\mathcal{M}|^2$ in the above equation contains the information about the interaction concerned. In a $P + K \rightarrow P' + K'$ scattering process, the energy and momentum variables are denoted as $X = (E_X, \vec{X})$, (where $X = P, K, P', K'$). The thermal phase space contains the information of elastic scattering processes (Fig.(1)) and its form changes with the nature of the scatterings. The details of phase-space factor for different processes will be discussed later in the text.

In the relaxation time approximation, Eq.(1) can be expressed as,

$$\frac{\partial \delta f_p}{\partial t} = -\mathcal{C}[f_p] = -\delta f_p \Gamma(p). \quad (3)$$

where $\Gamma(p)$ is the particle interaction rate, given by

$$\Gamma(p) = \frac{1}{2E_p} \int \frac{d^3k}{(2\pi)^3 2k} \frac{d^3p'}{(2\pi)^3 2E'_p} \frac{d^3k'}{(2\pi)^3 2k'} [PSF] (2\pi)^4 \delta^4(P + K - P' - K') \frac{1}{2} \sum_{spin} |\mathcal{M}|^2. \quad (4)$$

The heavy quark energy loss ($-dE/dx$) is then obtained by averaging over the interaction rate times the energy exchange per scattering and dividing by the velocity of the injected heavy quark,

$$\frac{dE}{dx} = \frac{1}{v_p} \int d\Gamma \omega. \quad (5)$$

The factor ω in Eq.(5) is essential in making dE/dx finite within resummation perturbation theory. The calculation of the interaction rate mentioned in Eq.(4), using tree level diagram, suffers quadratic infrared divergence. But in case of energy loss the extra ω factor softens the infrared divergence to only logarithmic. On the other hand, the resummed effective boson propagator makes Γ to be only logarithmically divergent which in turn makes $-dE/dx$ finite [8, 9]. The energy loss of a heavy-quark propagating through a hot quark-gluon plasma can be calculated either from the field theory approach or using effective kinetic theory. In the present paper we follow the latter one.

In order to estimate the charm quark energy loss it is necessary to have an idea of number of scattering centers present in the bath. It is well known that $\Gamma = n\sigma v$, where n is the density of the plasma particles, σ is the collision

Temperature (GeV)	$n_q + n_{\bar{q}}(fm^{-3})$	$n_g(fm^{-3})$	$n_Q + n_{\bar{Q}}(fm^{-3})$
0.3	7.70374	6.8478	0.5795
0.4	18.2607	16.2317	2.5511
0.5	35.6655	31.7026	7.3500
0.6	61.6299	54.7822	16.0630

TABLE I: Variation of number density of heavy quarks, light quarks and gluons with temperature

cross section and v is the velocity of the particle, which is equal to the velocity of light in case of relativistic particles [27]. The number density of charm quarks, light quarks and gluons present in the medium has been estimated by the following formula [28],

$$n_i = \frac{g_i}{(2\pi)^3} \int_0^\infty \frac{d^3p}{e^{E_i/T} \pm 1} \quad (6)$$

where, g_i is the degeneracy factor, E_i is the total energy of the particles ($i = Q, q, g$). In Table.(I) the variation of the number densities with the temperature of the medium can be observed. From the table it is evident that at temperatures relevant to LHC energies heavy quark density is quite significant along with light quarks and gluons. Hence, to construct a consistent formalism of heavy quark energy loss it is indeed necessary to incorporate the scatterings of injected parton with heavy quarks present in the medium. In the following section, we compute the contribution of heavy quark scatterings to the total energy loss.

A. Contribution of $QQ \rightarrow QQ$ scatterings

In this section, we illustrate the energy loss where the heavy quark (p) interacts with the thermal heavy quarks of momentum k . Following Eq.(5) the explicit form of heavy quark energy loss turns out to be,

$$\left(-\frac{dE}{dx}\right)_{QQ \rightarrow QQ} = \frac{1}{v_p E_p} \int_{p'} \int_k \int_{k'} (2\pi)^4 \delta^4(P + K - P' - K') \frac{1}{2} \sum_{\text{spins}} |\mathcal{M}|^2 \omega [PSF], \quad (7)$$

where, $\omega = (E_p - E_{p'})$ is the exchanged energy in an elastic scattering and $\int_{p'}$ denotes $d^3p'/(2E_{p'}(2\pi)^3)$. The above expression has been obtained by inserting the factor ω in Eq.(4) and multiplying by a factor of 2 to consider both the quark and the anti-quark scatterings ($Q\bar{Q} \rightarrow Q\bar{Q}$). Eqn.(7) is a general expression and is true for all kind of scatterings suffered by the heavy quark with the particles in the medium. The t -channel contribution of the matrix amplitude gives a contribution proportional to $\int dq/q^3$ to the Eqn.(7). This factor multiplied with the energy transfer ($-q \leq \omega \leq q$) softens the divergence to a logarithmic one. Further, self energy appearing on the exchange line cuts off this logarithmic divergence to give a term $\sim \ln(q_{\text{max}}/m_D)$ where $q_{\text{max}}(\sim \sqrt{E_p T})$ is the maximum momentum transfer per scattering and $m_D(\sim gT)$ is the Debye mass. Thus the logarithmic contribution is $\sim \ln(1/g) \gg 1$ for $g \ll 1$. This kind of leading log treatment extracts the coefficient of the logarithmic divergence which we have followed in our calculations to give results upto leading logarithmic accuracy. It might be mentioned here that the energy loss receives dominant contribution when the transferred momentum is assumed to be soft ($0 < q < m_D$) and $q \ll T, p, k$ which is precisely our kinematical domain for leading logarithmic calculation [29, 30].

In case of heavy and light quark interaction, the possibility of back scatterings in phase space factor ($[PSF]$) can be excluded. However, for the collision between heavy quarks one has to retain this process along with the forward one. This $[PSF]$ factor is then given by [6],

$$[PSF] = f_{E_k}(1 - f_{E_{k'}})(1 - f_{E_{p'}}) + (1 - f_{E_k})f_{E_{k'}}f_{E_{p'}} \quad (8)$$

where the first part of the above expression corresponds to forward scattering and the later part is included for back scattering contribution. Thus, we have,

$$\begin{aligned} [PSF] &= (f_{E_k} - f_{E_{k'}}) \left[1 + \bar{f}_{q_0} - f_{E_{p'}} \right] \\ &\simeq -\frac{df_{E_k}}{dE_k} q_0 \left[\frac{T}{q_0} + \frac{1}{2} \right], \end{aligned} \quad (9)$$

where, \bar{f}_{q_0} is the boson distribution function and is given by $\bar{f}_{q_0} = (\exp(q_0/T) - 1)^{-1}$ and $q_0 = \omega$.

The diagrams required for the calculation of the heavy quark energy loss are given in Fig.(1). It is to be noted that all these diagrams contribute at leading log order. Among these set of diagrams, the first one has not been calculated yet which is the main focus of this present paper. Apart from these diagrams, there is contribution from the s – *channel* scattering process which infact contribute at the same order in α_s as the t – *channel* one. Thus, for consistency, we have outlined the calculation for the s – *channel* in the Appendix. However, the contribution from the s – *channel* is suppressed in comparison to the t – *channel* which will be discussed in detail in the Results section.

In this section we present the derivation of heavy quark energy loss in the soft regime defined earlier as $|q| \ll |q^*|$ for the t – *channel* process. The soft contribution to the energy loss is evaluated in the region of phase space where the exchanged gluon has momentum of the order of gT . In this kinematical region, the gluon propagator has to be modified using the HTL resummation method in order to incorporate the in-medium effects.

In Eq.(7), the 3-momentum delta function is used to eliminate the p' integral,

$$\int d^3p' \delta^{(3)}(p + k - p' - k') = 1. \quad (10)$$

Next, we introduce an energy variable ω in the integrand of Eq.(7),

$$\delta(E_p + E_k - E_{p'} - E_{k'}) = \int_{-\infty}^{\infty} \delta(E_p - E_{p'} - \omega) \delta(\omega - E_{k'} + E_k) d\omega. \quad (11)$$

Two delta functions of the energy variable can then be written as,

$$\begin{aligned} \delta(E_p - E_{p'} - \omega) &= \frac{E_{p'}}{E_p} \delta\left(\omega - \vec{v}_p \cdot \vec{q} - \frac{t}{2E_p}\right) \\ \delta(\omega - E_{k'} + E_k) &= \frac{E_{k'}}{E_k} \delta\left(\omega - \vec{v}_k \cdot \vec{q} + \frac{t}{2E_k}\right), \end{aligned} \quad (12)$$

where, $\vec{q} = \vec{p} - \vec{p}' = \vec{k}' - \vec{k}$ and $\vec{v}_k = \vec{k}/E_k$. From this point it is convenient to change the integration variables from k, k' to k and q respectively. Using the expressions of the δ functions given above, the energy loss of the heavy quark given in Eq.(7) is written as,

$$\begin{aligned} \left(-\frac{dE}{dx}\right) \Big|_{QQ \rightarrow QQ}^{\text{soft}} &= \frac{(2\pi)^4}{(2\pi)^9 E_p^2 3.2 v_p} \int d^3k \int d^3q \int_{-\infty}^{\infty} d\omega \left[\frac{E'_p E'_k}{E'_p E_k E'_k E_p E_k} \right] [PSF] \\ &\quad \delta\left(\omega - \vec{v}_p \cdot \vec{q} - \frac{t}{2E_p}\right) \delta\left(\omega - \vec{v}_k \cdot \vec{q} + \frac{t}{2E_k}\right) \omega |\mathcal{M}|^2. \end{aligned} \quad (13)$$

In order to proceed further, it is necessary to introduce the form of the interaction. In the Coulomb gauge the matrix element \mathcal{M} for the $QQ \rightarrow QQ$ process can be expressed as follows [8],

$$\mathcal{M} = g^2 D_{\mu\nu}(q) \bar{u}(p', s') \gamma^\mu u(p, s) \bar{u}(k', \lambda') \gamma^\nu u(k, \lambda), \quad (14)$$

where α_s is the strong coupling constant. In the above mentioned gauge, only non-vanishing components of the bosonic propagator are,

$$\begin{aligned} \Delta^{00}(Q) &= \Delta_L(q_0, q), \\ \Delta^{ij}(Q) &= \Delta_T(\delta^{ij} - \hat{q}^i \hat{q}^j). \end{aligned} \quad (15)$$

Δ_L and Δ_T are the longitudinal and transverse components of the boson propagator and are given by [31],

$$\begin{aligned} \Delta_L(Q) &= \frac{-1}{q^2 + m_D^2 (1 - \frac{x}{2} \log(\frac{x+1}{x-1}))} \\ \Delta_T(Q) &= \frac{-1}{q_0^2 - q^2 - \frac{m_D^2}{2} \left(x^2 + \frac{x(1-x^2)}{2} \log(\frac{x+1}{x-1}) \right)}, \end{aligned} \quad (16)$$

where, m_D is the Debye mass and $x = \omega/q$.

Following Eq.(15) the non-zero components of the matrix element are [32],

$$\begin{aligned} \mathcal{M} &= g^2 \Delta_L(q) \bar{u}(p', s') \gamma^0 u(p, s) \bar{u}(k', \lambda') \gamma^0 u(k, \lambda) \\ &\quad + g^2 \Delta_T(q) (\delta^{ij} - \hat{q}^i \hat{q}^j) \bar{u}(p', s') \gamma^i u(p, s) \bar{u}(k', \lambda') \gamma^j u(k, \lambda). \end{aligned} \quad (17)$$

The matrix element given above has to be squared, averaged over initial spin s of the jet and summed over final spins. After evaluating the Dirac traces, we obtain,

$$\begin{aligned} \frac{1}{2} \sum_{spins} |\mathcal{M}|^2 = 32g^4 E_p^2 \Big\{ & |\Delta_L(Q)|^2 E_k^2 + 2E_k |\vec{k}| [(\vec{v}_p \cdot \hat{k}) - (\hat{q} \cdot \hat{k})(\hat{q} \cdot \vec{v}_p)] \text{Re}[\Delta_L(Q)\Delta_T(Q)^*] \\ & + |\Delta_T(Q)|^2 |\vec{k}|^2 [(\vec{v}_p \cdot \hat{k}) - (\hat{q} \cdot \hat{k})(\hat{q} \cdot \vec{v}_p)]^2 \Big\}. \end{aligned} \quad (18)$$

While, writing the above equation it has been assumed that leading logarithmic order contributions come from the region where the exchanged energy ω is small. Hence, $E'_p \simeq E_p$ and $E'_k \simeq E_k$. The soft contribution to the heavy quark energy loss then reduces to,

$$\begin{aligned} \left(-\frac{dE}{dx}\right) \Big|_{QQ \rightarrow QQ}^{soft} = \frac{g^4 C_F}{4v_p^2 \pi^3} \int dq \int k dk \frac{1}{E_k} \int_{-v_p q}^{v_p q} \omega^2(-) n'_F(E_k) d\omega \\ \times \left\{ |\Delta_L(Q)|^2 \frac{E_k^2}{v_k} + |\Delta_T(Q)|^2 k^2 \frac{1}{2v_k} \left[1 - \frac{\omega^2}{(v_k q)^2}\right] \left[v_p^2 - \frac{\omega^2}{(v_k q)^2}\right] \right\}. \end{aligned} \quad (19)$$

The above equation has been derived by using the following integrals over the angles of k ,

$$\begin{aligned} \int \frac{d\Omega_k}{4\pi} \delta(\omega - \vec{v}_k \cdot \vec{q}) &= \frac{1}{2v_k q}; \\ \int \frac{d\Omega_k}{4\pi} \delta(\omega - \vec{v}_k \cdot \vec{q}) \left[\vec{v}_p \cdot \hat{k} - \frac{\omega}{v_k q} (v_k \hat{q}) \cdot \hat{k} \right] &= 0; \\ \int \frac{d\Omega_k}{4\pi} \delta(\omega - \vec{v}_k \cdot \vec{q}) \left[\vec{v}_p \cdot \hat{k} - \frac{\omega}{v_k q} (v_k \hat{q}) \cdot \hat{k} \right]^2 &= \frac{1}{4v_k q} \left[1 - \frac{\omega^2}{(v_k q)^2}\right] \left[v_p^2 - \frac{\omega^2}{(v_k q)^2}\right]. \end{aligned} \quad (20)$$

Further evaluation of $(-dE/dx)$ in Eq.(19) cannot be performed analytically and has to be solved numerically.

It is to be noted that contribution from the integration domain where screening effect is absent can be extracted from Eq.(19) by putting screening mass to zero in the denominator of the propagator [33]. Final result of heavy quark energy loss scattering off thermalized charms in the medium is obtained by adding both the soft and hard contributions,

$$-\frac{dE}{dx} \Big|_{QQ \rightarrow QQ} = -\frac{dE}{dx} \Big|_{QQ \rightarrow QQ}^{soft} + -\frac{dE}{dx} \Big|_{QQ \rightarrow QQ}^{hard} \quad (21)$$

In this regard it would be worthwhile to mention the contribution of scatterings of heavy quark with other particles of the medium. The results for scatterings with light quarks can be obtained from Eq.(21) in the limit $v_k \rightarrow 1$ and the result matches with the findings of Ref.[9]. The contribution of $Qg \rightarrow Qg$ scatterings can be read from Eqs.(1), (6) and (7) of Ref.[9]. Hence, the complete expression for heavy quark energy loss can be obtained by adding all possible scatterings mentioned in Eq.(21) and in Ref.[9].

B. Implementation of running coupling

In the above calculations, we have explicitly assumed that the value of QCD coupling α_s is kept fixed. However, an effective calculation of the cross-sections for the process $QQ(\bar{Q}) \rightarrow QQ(\bar{Q})$ and estimation of the energy loss of the heavy quark can be performed taking into account the running coupling. In this work, we incorporate the effective coupling on all order resummations of perturbation theory including all non-perturbative effects as observed in Ref.[22, 23, 26] to calculate the energy loss. The transition from α_s to the running regime (α_{eff}) is stated as [22, 23, 26],

$$\alpha_s \rightarrow \alpha_{eff}(Q^2) \quad (22)$$

where,

$$\alpha_{eff}(Q^2) = \frac{4\pi}{\beta_0} \begin{cases} L_-^{-1} & Q^2 < 0 \\ \frac{1}{2} - \pi^{-1} \arctan(L_+/\pi) & Q^2 > 0 \end{cases} \quad (23)$$

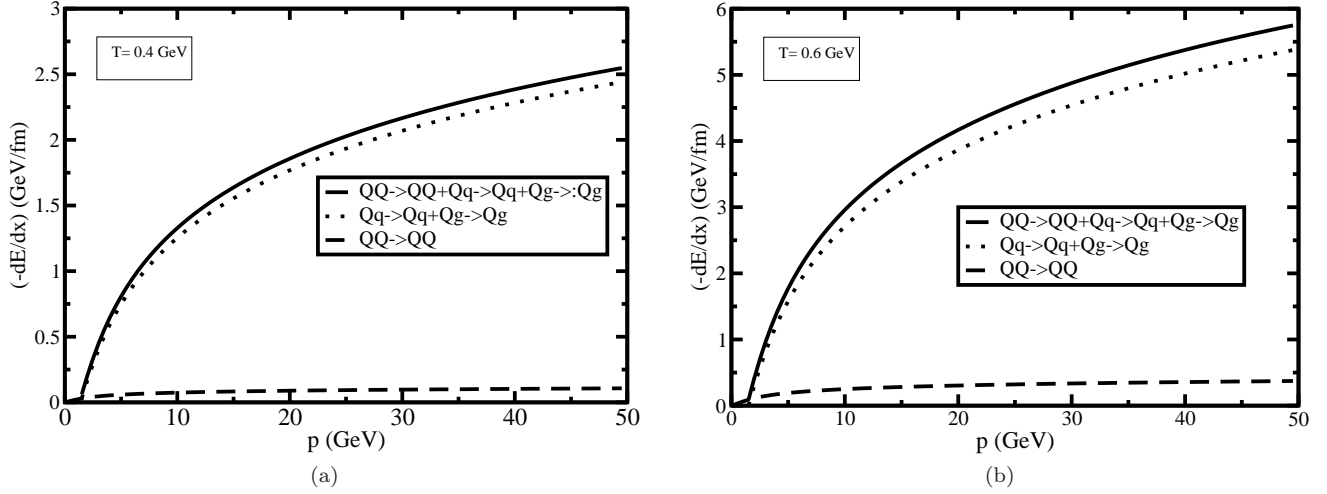


FIG. 2: Energy loss dE/dx of a charm quark as a function of its momentum for $T = 0.4$ GeV (a) and $T = 0.6$ GeV (b).

with $Q^2 = \omega^2 - q^2$, $\beta_0 = 11 - \frac{2}{3}n_f$ and $L_{\pm} = \ln(\pm Q^2/\Lambda^2)$ with $\Lambda = 0.263$ GeV. Moreover, we have also treated Debye mass (m_D) to be a function of both Q^2 and T , i.e.,

$$m_D^2 \equiv m_D^2(T, Q^2) = 4\pi\alpha_{eff}(Q^2)(1 + n_f/6)T^2 \quad (24)$$

The results for the energy loss of the heavy quark with the inclusion of running coupling are presented in the following section.

II. RESULTS

In the present paper we calculate the energy loss of a heavy quark in a medium where, in addition to the light quarks and gluons, thermalized heavy quarks are also present. The heavy quark loses energy in the hot medium *via* all t , s and u channel processes. In Fig.(2) the total heavy quark energy loss due to scatterings with medium particles has been compared with the known result of light quarks and gluons scatterings [9]. We also plot the contribution of heavy quark scatterings off thermalized heavy quarks in the medium. In this calculation, the momentum has been scaled to an upper limit of $q_{max} = \sqrt{4E_p T}$ in compliance with the results in [8]. With our present calculation, we present plots of $-dE/dx$ with the momentum, considering the temperatures of 400 MeV and 600 MeV respectively relevant to the plasma temperature produced at LHC. For the plots the heavy quark mass has taken to be 1.25 GeV and strong coupling constant $\alpha_s = 0.3$.

From the two plots in Fig.(2) it is evident that the contribution to the energy loss due to $QQ \rightarrow QQ$ scatterings increases with temperature like other two contributions. The observation is consistent with the earlier findings of number densities in the current paper. Increase in temperature increases number densities which in turn increases interaction rate as well as particle energy loss. It is observed that by including the process $QQ \rightarrow QQ$ the total heavy quark energy loss increases by 5% and 8% for temperatures 400 MeV and 600 MeV respectively at a momentum of 25 GeV. We have assumed a fixed value of the coupling constant for estimation of these results. Now, using the expression of α_{eff} as in Eq.(23), we evaluate the energy loss with charm quarks as particles of the medium. In the left panel of Fig. (3), a comparative study has been presented of the charm quark energy loss due to scattering with another heavy quark with constant and running coupling for a temperature of 0.4 GeV. In the right panel, similar comparisons have been performed for a fixed temperature of 0.6 GeV. In both of these panels, we find that the energy loss of the heavy quark under the inclusion of the t -channel $QQ \rightarrow QQ$ scattering, increases with temperatures as already obtained in the constant α_s case. We also find that the energy loss is greater when the coupling constant is taken to be running (Eq. (23)) as compared to the fixed one. These findings are consistent with the results obtained in Ref.[14, 22, 23]. In addition, we also calculate In Fig.4, we have shown the contribution of the scattering process in the s -channel ($Q\bar{Q} \rightarrow g \rightarrow Q\bar{Q}$). A brief calculation of this process has been given in the Appendix. For a typical momentum of 25GeV, we find that the s -channel contribution is $\sim 0.2\%$ (for both $T=0.4$ GeV and 0.6 GeV) to the total energy loss of the heavy quark with s -channel and t -channel combined. We reconfirm that the relative contribution of the s -channel is significantly lower than the corresponding t -channel processes that we

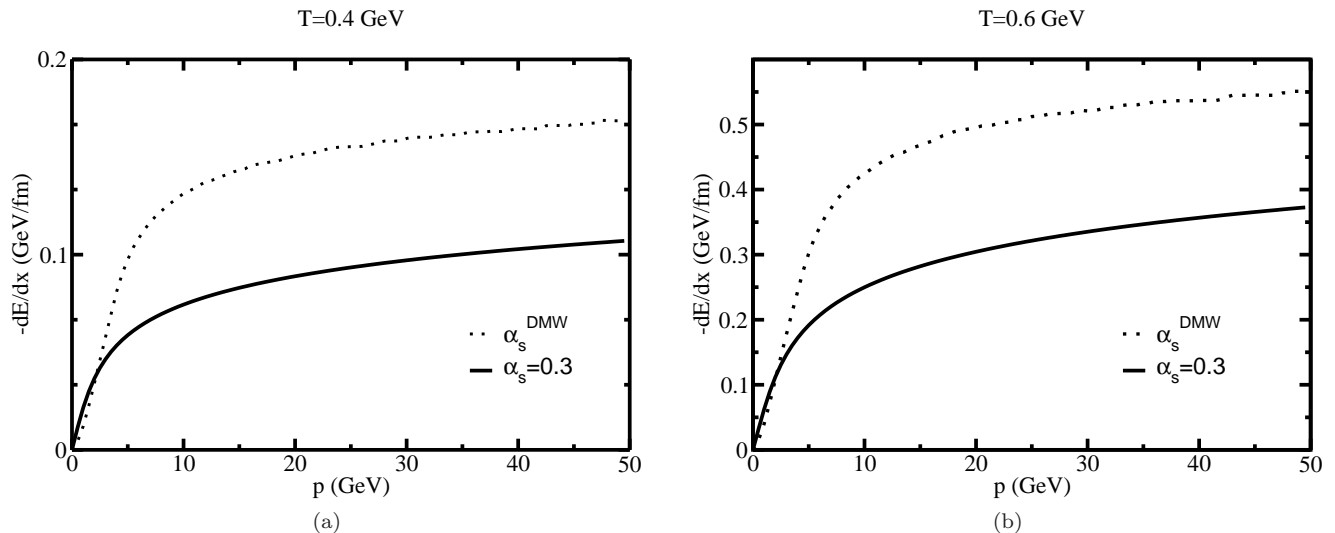


FIG. 3: Comparison of running coupling (α_{eff}) on energy loss for $QQ \rightarrow QQ$ scatterings at 0.4 GeV (a) and at 0.6 GeV (b) with the fixed value of the coupling constant (α_s).

have considered for our calculation of the energy loss of the heavy quark and hence can safely be ignored[29, 30].

III. SUMMARY AND CONCLUSIONS

In the present study, we have discussed the theory of heavy quark energy loss in a hot QCD plasma with specific emphasis on the impact of thermalized charms on the heavy flavor energy loss. In all the previous calculations of charm quark energy loss it has been assumed that the thermalized partonic medium is devoid of heavy quarks and consists of only light quarks and gluons. But the recent ALICE data has shown non-zero elliptic flow for J/ψ which is possible only if charm quarks gets thermalized in the medium. Hence, we have elucidated a consistent formalism of heavy quark energy loss, where all the possible scatterings with the particles and antiparticles of the medium ($Qq \rightarrow Qq$, $Qg \rightarrow Qg$ and $QQ \rightarrow QQ$) have been taken into consideration. From the numerical studies presented in the paper it is observed that the $QQ \rightarrow QQ$ scattering has a modest effect on the charm quark energy loss. It has also been observed that with the increase in temperature heavy quark energy loss due to $QQ \rightarrow QQ$ scattering increases thereby enhancing the total energy loss. In addition, the heavy quark energy loss increases fairly under inclusion of running coupling. These observations are consistent with the nature of number densities of plasma particles with temperature. In fact, this mechanism proves to be quite an efficient one for the energy transfer into the plasma which might have possible implications in the explanation of the regeneration of J/ψ at LHC. From the observables point of view we know that final heavy quarks are tagged in the heavy ion collision experiments to measure heavy flavour elliptic flow and nuclear modification factor. Now, in these experiments another possible source of heavy quarks could be scattering of high p_T gluons with thermalized charm quarks which contribute to produce high p_T D-mesons. Introduction of this process in the present calculation is a delicate issue. It is also very difficult to disentangle the high p_T heavy quark jet scattered from a thermal heavy quark and high p_T heavy quark jet produced from $gQ_{Th} \rightarrow gQ$. Thus, we do not address this possibility in the present work. In this paper our main concern has been to develop a consistent theoretical formalism of heavy quark energy loss with all possible scatterings. Effects of current findings on different physical observables at LHC will be reported elsewhere.

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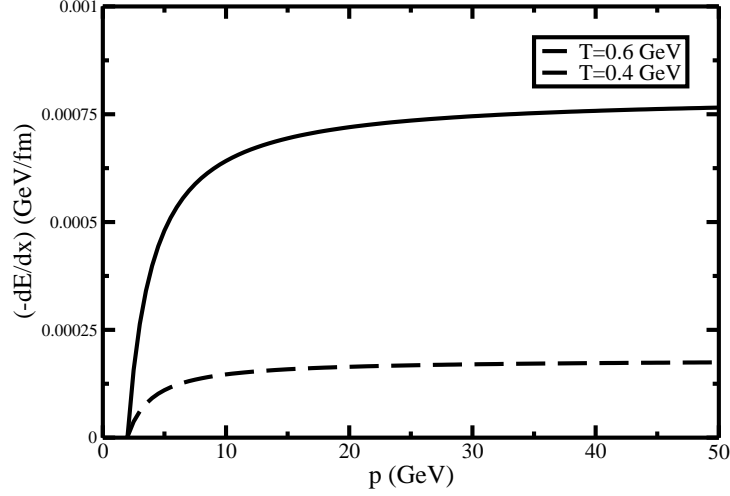


FIG. 4: s - channel contribution for the process $Q\bar{Q} \rightarrow Q\bar{Q}$ scatterings at 0.4 GeV and at 0.6 GeV with the fixed value of the coupling constant (α_s).

IV. APPENDIX

We briefly outline the calculation of the s - channel scattering process. Following the steps in [13], Eq.7 is modified for s - channel as,

$$\left(-\frac{dE}{dx}\right)_{Q\bar{Q} \rightarrow Q\bar{Q}(s\text{-channel})} = \frac{1}{v_p} \int \frac{d^3k [PSF]}{(2\pi)^3 2E_k} \int_0^{4m^2-s} du (4m^2 - s - u)(F_1)(F_2) |\mathcal{M}|^2 \quad (25)$$

where the functions are evaluated as,

$$F_1 = \left(1 - \frac{s - 2m^4/t}{s(1 + m^2/t) - 2m^4/t} \frac{E_k}{E_p}\right) \\ F_2 = \left(\frac{s(1 + m^2/t) - 2m^4/t}{(s(s - 4m^2))^{3/2}}\right) \quad (26)$$

and the matrix amplitude squared is given for the s - channel as[34],

$$|\mathcal{M}|^2 = \frac{64\pi^2 \alpha_s^2 (2m^2 - u)^2 + (2m^2 - t)^2 + 4m^2(s - 2m^2) + 8m^4}{9s^2} \quad (27)$$

This equation (25) cannot be solved analytically and has to be computed numerically. Now, we have taken the total contribution at α_s^2 for s-channel annihilation which are hard scatterings without self energy corrections.

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- [1] First Three Years of Operation of RHIC, Nucl. Phys. A **757** 1-283 (2005).
 - [2] J. Bjorken, (1982) FERMILAB-PUB-82-059-THY, FERMILAB-PUB-82-059-T .
 - [3] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, nucl-th/0302077.
 - [4] S. S. Adler et al., Phenix Collaboration, Phys. Rev. Lett. **96**, 032301 (2006).
 - [5] D. Bjorken, Fermilab Report No. PUB-82/59-THY, 1982 (unpublished).
 - [6] A. K. Dutt-Mazumder, J. Alam, P. Roy and B. Sinha, Phys. Rev. D **71**, 094016 (2005).
 - [7] P. Roy, J. Alam and A. K. Dutt-Mazumder, J. Phys. G **35**, 104047 (2008).
 - [8] E. Braaten and M.H. Thoma, Phys. Rev. D **44**, 1298(1991).
 - [9] E. Braaten and M.H. Thoma, Phys. Rev. D **44**, R2625(1991).
 - [10] M. G. Mustafa, Phys. Rev. C **72**, 014905 (2005).
 - [11] A. Peshier, Phys. Rev. Lett. **97**, 212301 (2006).
 - [12] M. Djordjevic, Nucl. Phys. A **783**, 197c (2007).
 - [13] S. Peigne and A. Peshier, Phys. Rev. D **77**, 014015 (2008).

- [14] S. Peigne and A. Peshier, Phys. Rev. D **77**, 014017 (2008).
- [15] A. Peshier, Phys. Rev. C **75**, 034906 (2007).
- [16] S. Sarkar, arXiv:**1403.1128v1**, (2014).
- [17] ALICE Collaboration, Phys. Lett. B **734**, 314 (2014).
- [18] E. Abbas et al. (ALICE Collaboration), Phys. Rev. Lett. **111** 162301 (2013).
- [19] E. Braaten and T. C. Yuan, Phys. Rev. Lett. **66**, 2183(1991).
- [20] E. Braaten and R. D. Pisarski, Phys. Rev. Lett. **64**, 1338(1990).
- [21] E. Braaten and R. D. Pisarski, Nucl. Phys. B **337**, 569(1970).
- [22] J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys. Rev. C **84**, 024908 (2011).
- [23] P. B. Gossiaux and J. Aichelin, Phys. Rev. C **78**, 014904 (2008).
- [24] L. Bhattacharya and P. Roy J. Phys. G **38**, 045001 (2011).
- [25] L. Tolos and J. M. Torres-Rincon, Phys. Rev. D **88**, 074019 (2013).
- [26] Yu.L. Dokshitzer, G. Marchesini, B.R. Webber, Nucl.Phys. B **469**, 93 (1996).
- [27] J. P. Blaizot and E. Iancu, Phys. Rept. **359**, 355 (2002).
- [28] P. Braun-Munzinger, J. Stachel, Phys. Lett. B **490**, 196 (2000).
- [29] P. Arnold, G. D. Moore and L. G. Yaffe, JHEP **11** (2000) 001.
- [30] P. Arnold, G. D. Moore and L. G. Yaffe, JHEP **05** (2003) 051.
- [31] M. Le Bellac, *Thermal Field Theory* (Cambridge University Press, 1996).
- [32] M. Djordjevic, Phys. Rev. C **74**, 064907 (2006).
- [33] M. Le Bellac and C. Manuel, Phys. Rev. D **55** (1997) 3215.
- [34] F. Halzen , A.D. Martin, *Quarks and Leptons* (New York: Wiley 1984).